Gamma-Ray Pulse Tube Cooler Development and Testing

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ABSTRACT

For a variety of space-science applications, such as gamma-ray spectroscopy, the introduction of cryogenic cooling via a cryocooler can greatly increase the potential science return by allowing the use of more sensitive and lower noise detectors. At the same time, the performance benefits must be carefully weighed against the implementation cost, any possibility of degraded detector performance associated with the operation of the cryocooler, and the requirement to achieve long life. This paper describes the development, test, and performance of a novel new low-cost, low-noise, high-reliability pulse tube cooler, designed specifically for highly cost-constrained, long-life space missions.

The developed cooler marries two technologies: a low-cost high-reliability linear compressor and drive electronics from the 1.75 W tactical Stirling cryocooler of DRS Infrared Technologies (formerly Texas Instruments), and an 80 K pulse tube developed specifically for the compressor by Lockheed Martin ATC. The successful new cooler achieves over 1.6 watts of cooling at 80 K at 23 W/W, and has the advantages of greatly reduced vibration at the coldtip and no life-limiting moving cold elements.

To achieve maximum life and low vibration, the compressor incorporates flat flexure springs for piston support and uses two opposing pistons in a head-to-head configuration with linear drive motors. The pulse tube is a compact U-tube configuration for improved integration and is mounted to the compressor in a split configuration with a transfer line.

INTRODUCTION

The object of this cooler development program was to make it possible to utilize high-resolution germanium (Ge) detectors for planetary gamma-ray spectroscopy on relatively low-cost space missions involving one- to two-year operational lifetimes. Use of a germanium detector cooled to around 80 K provides measurement sensitivities that are on average seven times greater than commonly used uncooled scintillation gamma-ray detectors.

Until now, radiative cooling to space has been the best method for weight-limited, long-duration planetary missions. Now, with reductions in size and power consumption, and improve-

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ments in reliability, miniature mechanical coolers offer an increasingly attractive alternative. Their use would eliminate the interface requirement for a three-axis stabilized spacecraft and a broad unobstructed view to space, and would allow experiments in environments where radiative coolers cannot function satisfactorily, notably in orbit around warm planets and on the surface of planets and moons. Comparisons of size, mass, duty cycle and operating temperature make mechanical cooling more attractive than radiative cooling for many planetary missions.

Developing a mechanically-cooled gamma ray spectrometer (GRS) for small, low-cost, planetary missions requires a small, long-life, low-cost cooler from which vibration, capable of inducing microphonics effects at the detector, has been eliminated. The cooler solution described here is to combine the compressor from a low-cost, miniature, high-reliability, commercially-available Stirling cycle tactical cooler, with a matched pulse tube expander made specifically for the compressor. The intended result is to produce a cooler that has minimal mechanical motion at the detector, retains the small mass and volume characteristics of the tactical cooler, and, thanks to recent improvements in pulse tube efficiency, requires a relatively low level of spacecraft power. The elimination of the tactical cooler's Stirling displacer is expected to also add to the reliability and lifetime of the cooler, and substantially reduce the vibration environment at the cold-load interface. The use of a commercially available compressor and the simplicity of the pulse tube design is expected to preserve most of the cost advantage of the tactical cooler relative to the sophisticated long-life space coolers. The same relative simplicity is also expected to translate into additional cost savings by allowing inexpensive tactical-cooler drive electronics to be used.

COMPRESSOR SELECTION AND DESIGN FEATURES

Central to achieving the cooler development objectives was the need to acquire a tactical cryocooler compressor with proven long-life potential, low vibration, and compatibility with the needed pulse tube expander in terms of swept volume and operating pressure. The specific design goal was to achieve > 1.1 watt of cooling at 80 K with a compressor specific power of less than 25 watts/watt.

An analysis of available tactical cooler compressors led to the selection of an advanced 1.75 W tactical Stirling cryocooler manufactured by DRS Infrared Technologies (formerly Texas Instruments). The particular model, shown in Fig. 1, is based on an advanced linear compressor with its two pistons operated head-to-head and supported on flexure springs to achieve long life and good vibration suppression. This new flexure-supported compressor is one of a family of advanced flexure-equipped compressors being developed to achieve extended-life tactical coolers.[1]

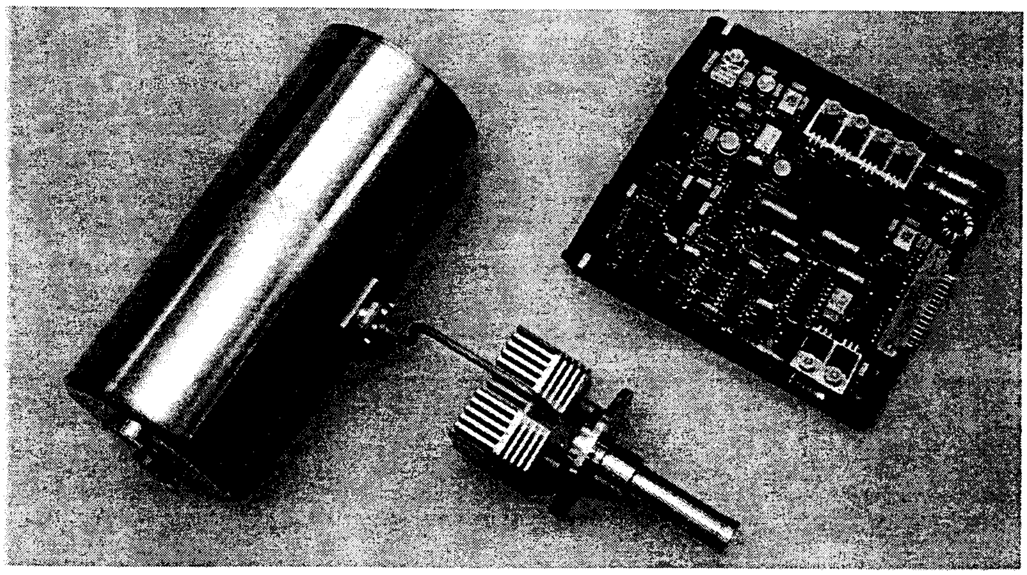

Figure 1. DRS 1.75 W tactical cooler with drive electronics.

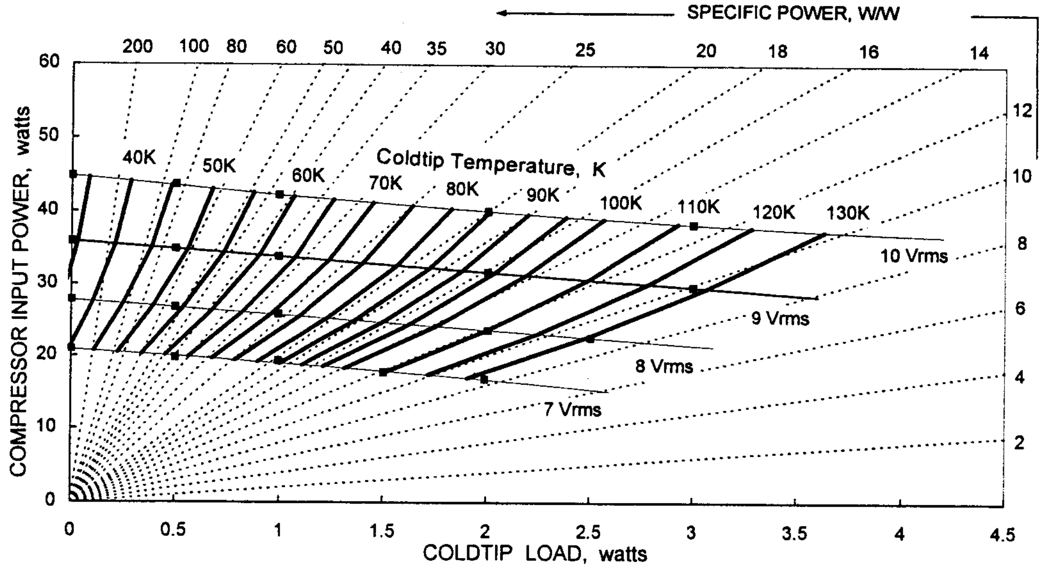

Figure 2. Refrigeration performance of the DRS 1.75 W Stirling cooler as a function of input drive voltage, coldtip temperature, and coldtip load.

The thermal performance of this cooler, using the Stirling expander shipped with the cooler, is shown in Fig. 2. The more conventional DRS 1.75 W cooler has similar performance, but uses helical coil springs to support the pistons and has a predicted life greater than 5000 hours. JPL has had good success using the conventional (non-flexure-spring) DRS 0.2-watt, 1-watt, and 1.75-watt Stirling coolers for a variety of low-cost, intermediate-life space missions.[2,3,4]

PULSE TUBE DESIGN AND CONSTRUCTION

The second task critical to achieving the required cooler performance was the development of a high efficiency pulse tube expander carefully matched to the compression attributes of the DRS compressor and the interface requirements of the JPL gamma-ray detector mounting system, shown schematically in Fig. 3. This task, carried out by Lockheed Martin Advanced Technology Center, involved first thoroughly characterizing the DRS compressor, then designing and fabricating a pulse tube consistent with the compressor and the gamma-ray detector cooling load and mounting interfaces. The chosen concept was the U-shaped pulse tube shown in Fig. 3.

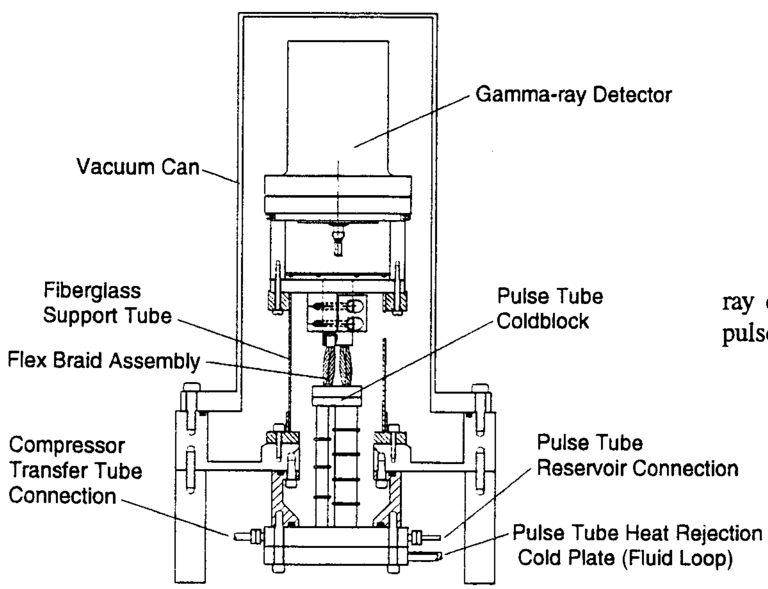

Figure 3. Schematic of gamma-ray detector test setup with integrated pulse tube expander.

Table 1. DRS 1.75-watt flexure-spring compressor parameters.

Mechanical spring K (N/m)	1.04E+04
Moving mass (kg)	0.28
Coil resistance (ohms)	1.3
Force constant (N/A)	10-11.3
Piston area (cm^2)	1.98
Max 0-P piston amplitude (mm)	5
Internal transfer line	2.56mm ID by 3.65 cm long

Compressor Characterization

To achieve an efficient design for the proposed pulse tube it was necessary to include an accurate model of the compressor's performance in the overall pulse tube design analysis. To acquire the needed data, the DRS flexure-bearing compressor was tested at Lockheed Martin ATC with dead volumes to determine its characteristics. Tests were performed using three different dead volumes (12.1cc, 22.8cc, and 28.9cc), and five different charge pressures (300psia, 200psia, 100psia, 50psia, and 5psia).

The compressor was driven with a current controlled amplifier with an input signal given by an HP signal generator. The power to the compressor was monitored with a Valhalla power meter, and a calibrated pressure transducer, mounted in the compression space, monitored the pressure.

The resonant frequency at each charge pressure was determined by a frequency sweep searching for the maximum voltage for a fixed drive current, for drive currents ranging from 0.1 A up to 1.3 A. At the resonant frequency, the current, voltage, power, and pressure amplitudes were recorded. Table 1 presents a summary of the compressor parameters (for each compressor half); most were determined from the measurements, while some were provided by DRS.

Compressor internal losses were also characterized to allow estimation of the expected efficiency of the overall pulse tube cryocooler. Because the compressor exit-passage parameters were designed for the standard DRS split-Stirling expander that has a small-diameter transfer line, somewhat higher losses were predicted when used with the pulse tube, which requires a larger transfer line. In the future, if more optimum performance from the compressor is desired, one should consider enlarging the internal flow passages to tailor the compressor for improved operation with a pulse tube.

Pulse Tube Design

To achieve an efficient design for the pulse tube, detailed thermodynamic simulations were conducted by Lockheed Martin of the entire cooler system. Key parameters included pulse tube geometries, transfer line diameter, fill pressure, operating frequency, piston stroke, and pulse tube reservoir-line tuning.

The resulting design was predicted to provide 1.2 W of cooling at 80 K with 30 W of total compressor power and a piston amplitude of 2.9 mm. Note that the piston amplitude is well below the maximum of 5 mm. The predicted cooling capacity is slightly higher than the required 1.1 W, and the predicted specific power of 25 W/W matches the design goal.

The largest uncertainty in the prediction was the internal losses within the compressor, which, in the dead volume tests, were particularly significant at high piston amplitudes. A conservative empirical model was used to represent the compressor flow losses in the analysis, which tended to reduce the piston amplitude in order to reduce the losses.

A series of parametric studies was performed to predict the sensitivity of the coldhead to operating conditions. The efficiency of the coldhead was found to be relatively insensitive to mass flow rates and frequencies, typical of other L-M pulse tubes. This indicates that the coldhead design was not significantly influenced by the particular model used for the compressor losses.

Figure 4 shows the (pressure-volume) PV specific power as a function of input power. As shown, the coldhead itself is predicted to have a PV specific power of 14 W/W at 80 K, comparable to other coldheads developed at Lockheed Martin ATC.[5,6] Lockheed's best in-line, high-

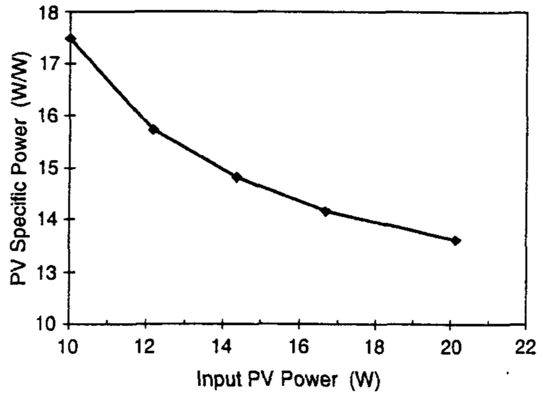

Figure 4. Predicted PV specific power as a function of input power.

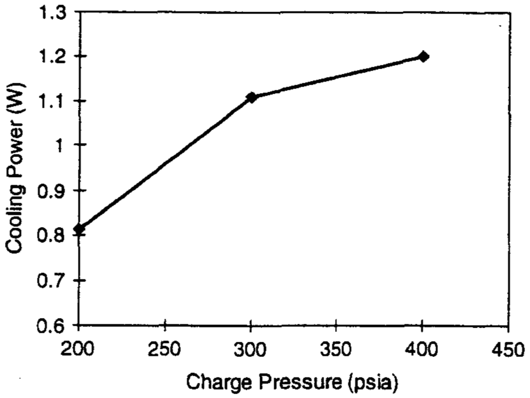

Figure 5. Predicted cooling power dependence on charge pressure.

capacity designs are typically 11-12 W/W. The slightly lower efficiency of this pulse tube is due in part to the U-tube configuration, the small diameter of the transferline internal to the compressor, and to the smaller cooling capacity. At the lower power levels, the efficiencies are still good, although slightly decreased from the higher power levels. At 10 W of PV power, the PV specific power is predicted to be around 17.5 W/W.

Figure 5 shows the predicted cooling power as a function of charge pressure at 30 W of compressor power. The frequency was varied for optimum performance, along with retuning of the impedances. The regenerator and pulse tube remained fixed in the analysis. This plot suggests that 400 psia would be a good working charge pressure, and shows that the cooler can tolerate a slight reduction in charge pressure down to 300 psia or so without serious reduction in performance. However, if the charge pressure is decreased down to 200 psia, the performance begins to seriously degrade. If the regenerator and pulse tube were to be redesigned for lower charge pressures, then the performance degradation would not be as severe as shown in Fig. 5.

The results of the overall simulation analyses indicated that the proposed coldhead should perform well over a range of conditions. This is significant in that the compressor loss mechanisms were not known in detail. Once the compressor and coldhead were integrated, it was expected that minor tuning of the overall system would be able to achieve a good match between coldhead and compressor.

Based on the modeling it was considered likely that the pulse tube would exceed the predicted efficiency, since a conservative model was used for the compressor losses, a conservative model was used for the motor force constant, and many Lockheed coldheads outperform their predictions. Thus, it was expected that the coldhead would provide in excess of 1.1 W of cooling at better than 25 W/W. In addition, the low design stroke would allow the cooler to be driven to substantially higher strokes and power levels, although at a somewhat higher specific power.

Pulse Tube Fabrication

Once the analyses and component designs were complete, the pulse tube cooler components were fabricated and assembled into a completed pulse tube expander. Figure 6 shows the piece parts ready for assembly, together with a completed pulse tube. Figure 7 shows the complete cooler setup during verification testing at Lockheed.

PULSE TUBE SYSTEM-LEVEL TESTING

After initial checkout and performance verification of the completed cooler at Lockheed Martin ATC, extensive performance characterization testing was carried out at JPL in preparation for planned tests to validate the vibration and EMI compatibility with an actual gamma-ray detector using the setup illustrated in Fig. 3.

Figure 8 presents the overall thermal performance measured at JPL as a function of coldend

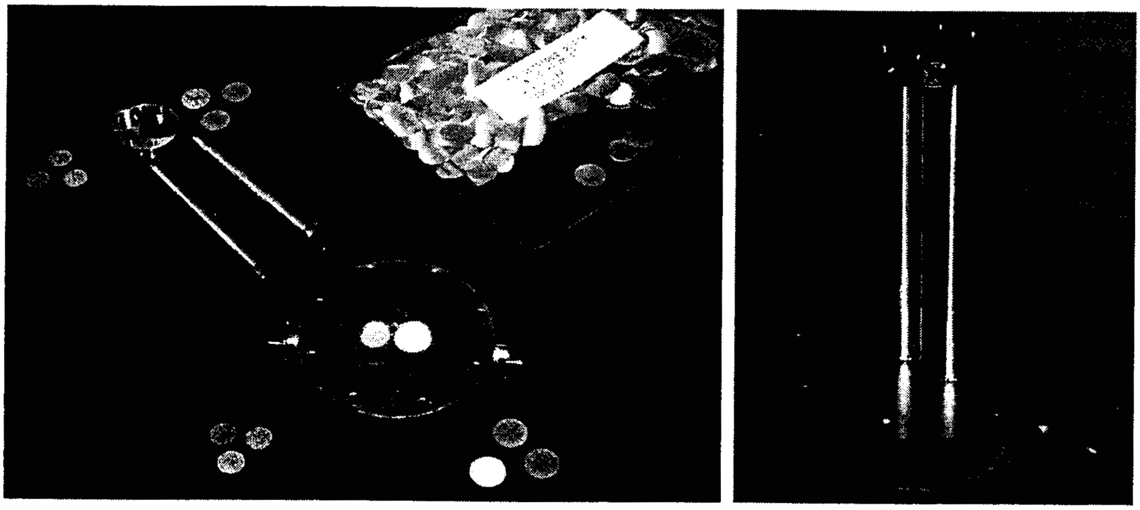

Figure 6. Pulse tube expander piece parts and final assembly.

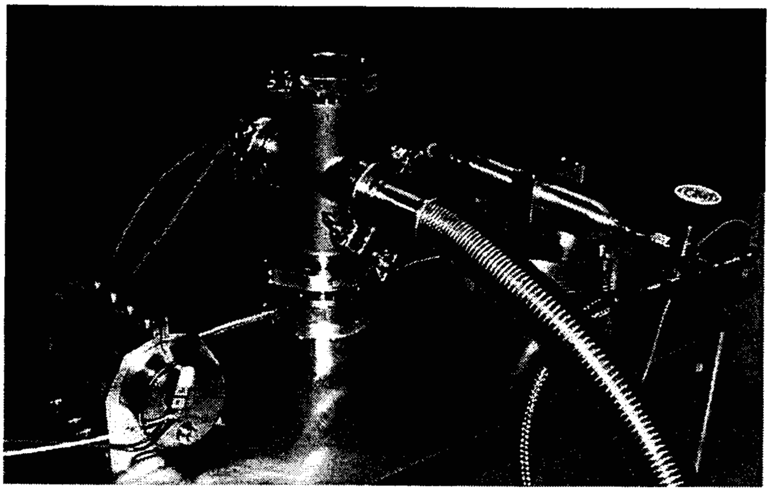

Figure 7. Completed pulse tube cooler with DRS compressor on the left, reservoir volume on the right, and pulse tube with vacuum bonnet assembly in the center.

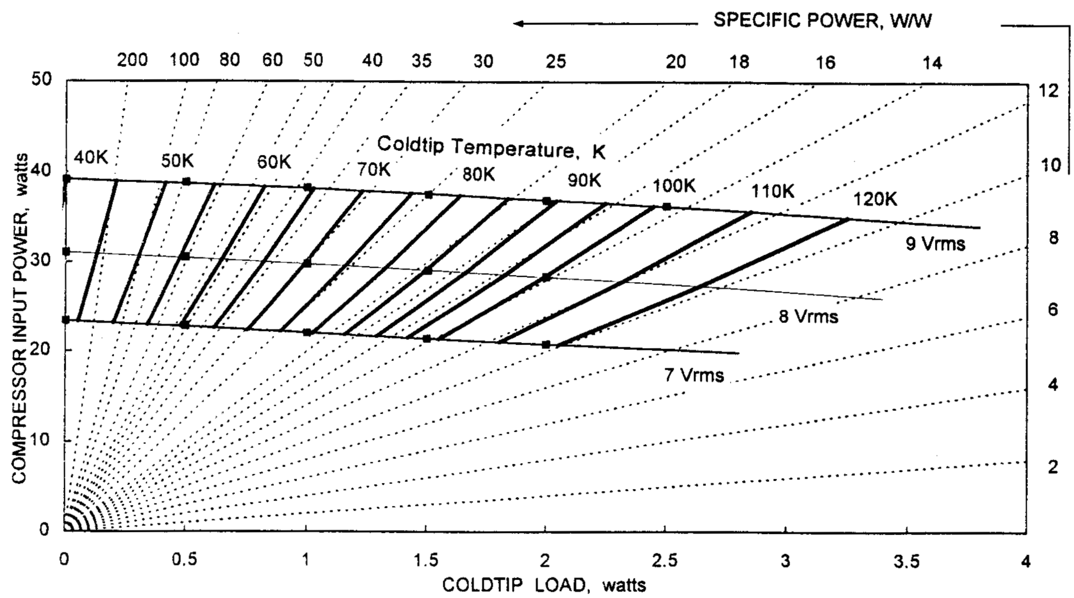

Figure 8. Refrigeration performance of the completed gamma-ray pulse tube cooler as a function of input drive voltage, coldtip temperature, and coldtip load.

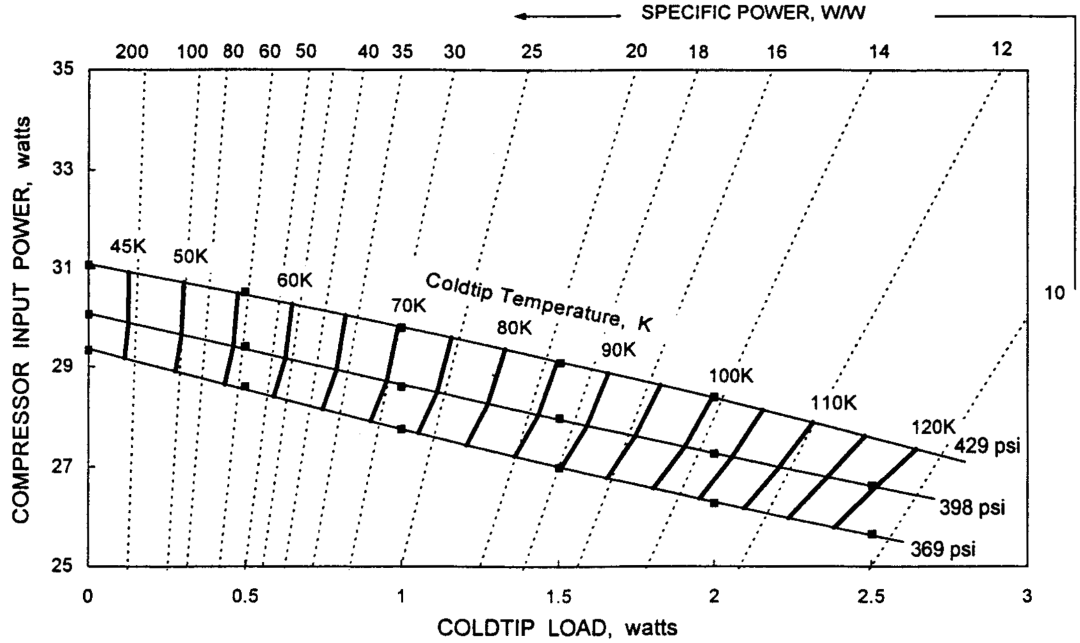

Figure 9. Refrigeration performance of the completed gamma-ray pulse tube cooler as a function of helium fill pressure.

temperature, coldend load, and input voltage (which is roughly proportional to stroke). Note that the specific-power performance at 80 K is around 22 W/W, which is better than the design goal of 25 W/W, and that the overall cooler capacity is also better than the design requirement, reaching over 1.6 watts at 80 K near full stroke (9 volts), in contrast to a requirement of 1.1 watt.

To confirm the cooler's predicted sensitivity to fill pressure and drive frequency, additional parametric testing was conducted with these parameters as variables. The measured performance, displayed in Figs. 9 and 10, confirm that fill pressure increases cooling capacity with minimal effect on efficiency, while drive frequency, once the pulse tube volumes are fixed, is a relatively sensitive parameter. For the as-fabricated pulse tube cooler, the best specific power is seen to occur at a frequency of around 42 Hz.

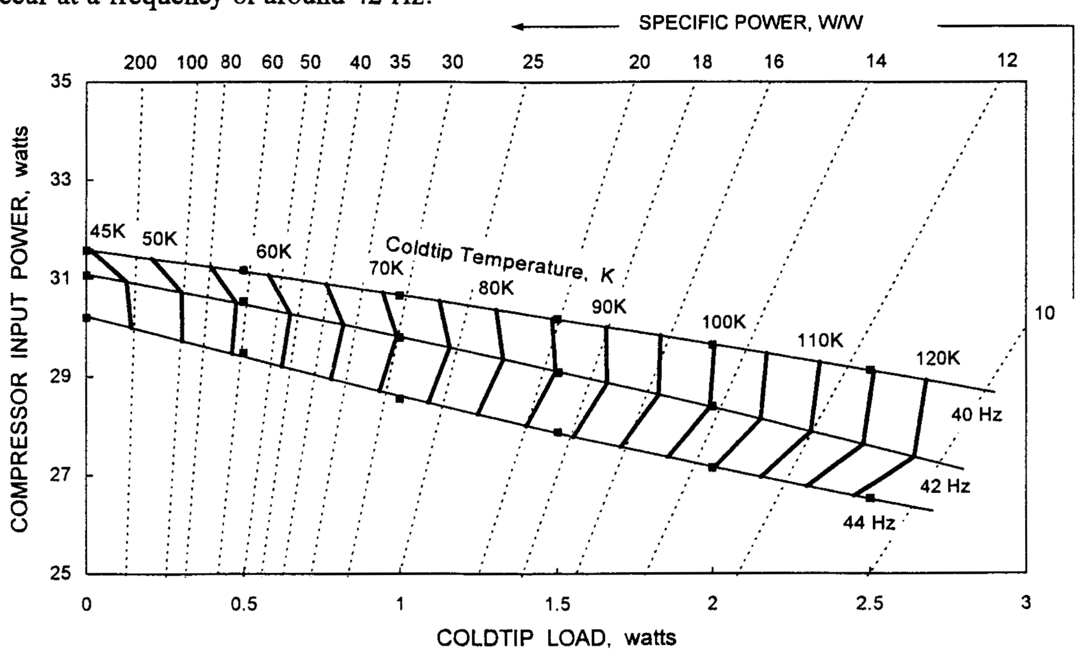

Figure 10. Refrigeration performance of the completed gamma-ray pulse tube cooler as a function of drive frequency.

SUMMARY AND CONCLUSIONS

This paper has described the development, test, and performance of a novel new low-cost, low-noise, high-reliability pulse tube cooler, designed specifically for highly cost-constrained long-life space missions such as planetary gamma-ray spectroscopy.

The developed cooler marries two technologies: a low-cost, high-reliability linear compressor and drive electronics from the 1.75 W tactical Stirling cryocooler of DRS Infrared Technologies, and an 80 K pulse tube developed specifically for the compressor by Lockheed Martin ATC. To achieve maximum life and low vibration, the compressor incorporates flat flexure springs for piston support and uses two opposing pistons in a head-to-head configuration with linear drive motors. The pulse tube is a compact U-tube configuration for improved integration and is mounted to the compressor in a split configuration with a transfer line.

The successful new cooler achieves over 1.6 watts of cooling at 80 K at 23 W/W, and has the advantage of greatly reduced vibration at the coldtip and no life-limiting moving cold elements.

ACKNOWLEDGMENT

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